3D Printed Medical Imaging Data:

A Tool to Supplement Doctor/Patient Communication

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Abstract

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This thesis proposes the application of 3D printed medical imaging data as a supplement to current visualization techniques employed by doctors for the purpose of patient communication and consent gathering. Contemporary visualization techniques are limited by two dimensional display formats, consequently restricting the efficacy of visualization aids provided to patients during the decision making process. This research leverages modern medical imaging modalities with 3D printing technology to generate physical replicas of individual patients' cardiac anatomy. An outline of the processing techniques involved is explained, and an overview of relevant 3D printing applications within medicine is given. The research project described was assessed using qualitative analysis by a panel of 7 physicians and clinicians from diverse medical disciplines. Semi-structured interviews were conducted with the panel in regard to the efficacy of 3D printed cardiac models as used to facilitate Doctor/Patient communication.

INTRODUCTION

1.1: Research Overview

The research outlined in this paper aims to evaluate the efficacy of patient specific 3D printed cardiac models when used to supplement contemporary medical visualizations for use in patient education and communication. This research focuses specifically on cardiac anatomy due to its high level of internal complexity and because of the overwhelming risk factors associated with cardiac illness and surgical treatment. I hypothesize that doctors will be better equipped to educate their patients through the use of physically accurate cardiac models specific to the patients' anatomy and pathology, thus empowering patients to make better informed decisions about their healthcare. To test this hypothesis, anonymized cardiothoracic CT scan data was used to derive a 3D model of the cardiac anatomy. This computer model was then 3D printed using a highly accurate polyjet printer. A diverse panel of physicians and clinicians provided qualitative analysis by way of semi-structured interviews to determine the model's accuracy to the scan data as well as its ability to bridge knowledge gaps between doctors and their patients.

Though this research is specific to the heart, the underlying process can be applied to any region of the anatomy that can be visualized through medical imaging and scanning modalities, thus offering a host of opportunities for similar applications and future research across a myriad of anatomical pathologies.

1.2: Patient Education & Health Literacy

With the movement toward patient centered care over the last several decades, patient education has become an increasingly integral part of the Doctor/Patient relationship [1]. For effective patient education to take place, it is crucial to establish good communication between healthcare providers and patients [2]. Research has shown that effective doctor/patient communication fosters greater adherence to treatment recommendations, reduces anxiety (for both the patient and the clinician), and results in better medical and psychological outcomes following a substantially invasive procedure [3].

Studies also suggest that a significant portion of patients have low levels of health literacy. This is especially problematic in instances of Shared Decision Making between doctor and patients [4]. To combat this, healthcare providers must find ways to provide patients with information in a way that is easily understood and invites participation and discussion. Higher health literacy results in patients being more involved and informed regarding important healthcare decisions [5].

One method of raising patient literacy and facilitating shared decision making is the use of Decision Aids and Evidence Based Patient Information packages [6]. These packages often consist of informative brochures, interactive DVDs and web applications, and are geared toward informing patients about 1) a pathologies natural course, 2) a comprehensive list of treatment options, 3) the probability of success or failure of medical intervention, as well as other relevant data which might concern the patient [6].

1.3 *2D versus 3D: Visual/Spatial Cognition*

Contemporary decision aids and patient information packages suffer from increasingly outmoded formats; i.e. printed brochures, pamphlets, and simple web pages. This is problematic because it limits the viewer's perception of the spatial elements in a given visualization, and can inhibit understanding of complex physical relationships [7]. This research seeks to mitigate these limitations based in a number of theoretical frameworks involving visual/spatial cognition which suggest that comprehension is improved when active control of physical objects is coupled with explicit guidance.

Howard Gardner's theory of Multiple Intelligences suggest that humans possess visual-spatial intelligence, and that certain concepts are best understood by visualizing related objects in space [8]. Psychologists have conducted studies which show that individuals achieve greater perceptual learning when given a physical control of the three-dimensional object in question [9].

Further research suggests that by actively manipulating an object individuals are able to gain a better understanding of concepts related to that object when coupled with explicit guidance [10]. The research proposed in this paper leverages these concepts and theories to overcome limitations associated with two-dimensional (printed on paper/displayed on screen) materials provided by doctors to aide patient decision making.

1.4: 3D Printing Medical Image Data

Computer graphics are a well established tool in aiding medical visualization. The ability to present three-dimensional anatomical information using computer generated imagery offers a vast improvement over traditional medical illustration. Affordances of modern medical imaging software include 3D volume rendering; a process by which a two-dimensional medical imaging dataset can be quickly and easily converted into a three-dimensional graphical representation of that dataset, or parts thereof. These techniques, however, are limited in that their final output is restricted to the two-dimensional nature of the final display device [11].

Recent developments in 3D printing technology have allowed for the physical realization of computer generated 3D models. The resulting physical models are not impeded by two-dimensional displays, allowing for improved understanding of the object's spatial properties. Furthermore, 3D printed physical models offer tactile information and haptic feedback that two-dimensional displays cannot.

By leveraging computer generated medical visualization with the capabilities of 3D printing, it is possible to retain the benefit of three-dimensional computer graphic content without the restrictions of two-dimensional output displays. Because 3D printers are able to create objects without regard to complexity, the intricacy of anatomical structures is not a limiting factor in manufacturing the physical object (unlike other means of manufacture).

3D printing relies on computer generated 3D models, which can be derived a number of ways. Users can generate 3D models either procedurally or by hand using 3D modeling software such as Maya or Modo, or inside CAD applications like Solidworks. Additionally, it is possible to acquire 3D model data through 3D scanning techniques, of which there are many.

Several methods of 3D scanning are heavily utilized within medicine, such as Computer Tomography (CT) and Magnetic Resonance Imaging (MRI) (as well as many others). These imaging techniques have become invaluable tools for aiding doctors in the diagnosis and treatment of complex pathologies [12].

CT scans are made up of dozens of xray images; which are collected into a singular file in the DICOM format. Each image consists of a single thin “layer” of the overall scan area. DICOM viewing software can interpolate between each of these images to generate a three-dimensional representation of the collection of images [12, 13]. Therefore, it is possible to visualize the sum of the scan data as a singular 3D object inside the DICOM viewing software. This approach is called volume rendering [14]. Using image manipulation techniques, users can isolate specific areas of a patient’s anatomy captured in the scan, and view discrete regions of interest of the volume render in full 3D.

It is also possible to convert the 3D volume rendering created by the DICOM viewer into a 3D model which, after further processing, can be physically manifested by a 3D printer. This allows for 3D printed internal anatomical models which are highly accurate in scale and topology, and are specific to the individual patient’s scan data.

Such techniques have been employed by numerous researchers for use in a wide array of applications. These include diagnostics, surgical planning, visualization, prosthesis design, forensics, and many others. Despite the intended application, researchers agree that 3D printed models used for medical visualization provide distinct advantages over similar representations presented via two-dimensional media [7, 11].

The process of converting patient specific medical imaging data consists of three key steps. These include 1) data acquisition, 2) 3D model segmentation, and 3) 3D printing. While steps 1 and 3 in this process are relatively straightforward, much of the difficulty lies within step 2, during 3D model segmentation. Both medical scan data and printable models rely on their own universally accepted file formats (DICOM and .STL, respectively). The goal of the segmentation procedure is to procure the necessary .STL file from the source DICOM series. In the past, researchers have employed specialized medical imaging software as well as 3D animation production and CAD tools to obtain 3D printable models from medical scan data [7,15,16]. This research utilizes Mimics Innovation Suite to derive printable models using publicly available DICOM datasets made available by Osirix.

3D printing of medical imaging data offers exciting advancements in the field of medical visualization, and has been widely researched across a variety of disciplinary niches within medicine. The goal of this research project is to expand existing research to include patient communication as a valuable use for 3D printing of patients' imaging data within medicine.

II. RESEARCH QUESTION

2.1 Research Question

How can patient-specific 3D printed cardiac anatomy replicas supplement contemporary visualization techniques in aiding Doctor/Patient communication?

III. LITERATURE REVIEW

3.1: Spatial Reasoning & Visual Cognition

According to Howard Gardner's theory of multiple intelligences;

"Central to spatial intelligence are the capacities to perceive the visual world accurately, to perform transformations and modifications upon one's initial perceptions, and to be able to re-create aspects of one's visual experience".

Research grounded in this theoretical approach indicates that visual/ haptic feedback and the ability to manipulate an object in three-dimensional space facilitates the learning process [9, 15, 17].

Psychology research conducted in 1999 using 3D objects in a virtual space demonstrated that "active control of visual input during perceptual learning leads to more efficient object recognition" [9]. An experiment was conducted wherein subjects were asked to manipulate a 3D object on a computer screen, and then to later identify the same object presented in static views. The results of this experiment showed that individuals recognized novel objects after having manipulated these objects in three dimensional space, suggesting that individuals' perceptual knowledge is aided by controlling an object in such a way that conveys its structure.

Later research into Spatial Reasoning indicates that offering interactive control of an object does not always equal enhanced understanding. One study suggests that access to relevant information is just as important as active control of an object, and that individuals “may not always perceive the affordances of external visualizations without explicit instruction. [10].

In the context of doctor/patient communication, these studies reinforce the proposed theory that tactile physical objects could act as a powerful aid in raising healthcare literacy among patients, and that this is achieved through the support and guidance provided by their doctors.

3.2: Medical Imaging & Visualization

In the last decades of the 20^{th} century medical diagnostic imaging modalities advanced significantly, moving beyond image production to include image processing and computer aided diagnosis [12]. Two major advancements include MRI and CT scanning, which have become the gold standard in non-invasive perioperative and diagnostic imaging [13]. The strength of these modalities lies in their high level of accuracy in detailing internal anatomy as well as the amount of information they provide to doctors and clinicians.

Computer Tomography works by collecting a large number of X-rays from several angles. These X-ray images are then processed by a computer into three planar views: Axial (top down), Saggital (side view), and Coronal (front view). Each of these views are divided into many individual cross-sectional “slices”, or singular x-ray images.

The resolution of a CT scan is a function of the distance between each slice. Modern CT scanners are capable of achieving resolutions of around 0.6mm between each slice. Each slice within the scan provides highly detailed information about the internal anatomy; however, because of the fragmented nature of the CT scan, it can be difficult for untrained individuals to understand the entirety of the structure being represented.

Through the use of specialized software, it is possible to create a three-dimensional volume render of data collected during a CT scan [14, 18]. These volume renders are viewable in real time, and can be manipulated in a number of ways to isolate specific areas of the scan data for closer review. The volume render can also be used as the basis for 3D model generation [19].

The resultant 3D models can be used in numerous medical visualization applications across myriad disciplines. Research has indicated that in educational settings, 3D medical visualizations offer students greater understanding of complex anatomies and their relationship to one another, as well as the physical behavior of complicated pathologies [Silen, 2008]. Likewise, doctors are able to utilize these visualizations in aiding the identification and care of countless afflictions throughout the body [12, 13, 15].

A major drawback to three-dimensional medical visualizations is their dependence on two-dimensional output displays [7]. Whether it be a computer monitor, television screen, or printed page; the three-dimensional visualization is restricted to a singular perspectival view at a time. This can rob the viewer of a certain spatial understanding of the anatomies depicted, and can lead to misunderstandings of complex physical behaviors [17]. To overcome these drawbacks, extensive research has been conducted into 3D printing for medical visualization applications [7,11].

3.3: 3D Printing

3D Printing has been in existence since the mid 1980s. In the early 2000s, reductions in cost and advancements in technology facilitated the widespread proliferation of 3D printers. At present, countless models of 3D printers are available for both consumer level and industrial applications.

3D printing of medical imaging data has been the subject of numerous research endeavors. [7] These include (but are not limited to) educational visualization, diagnostic imaging, surgical planning, and prosthesis design.

Educational Visualization & Training

Historically, in order to train aspiring surgeons in the specifics of a given procedure or anatomical structure, the use of cadavers was employed. This solution is undesirable for a number of obvious reasons; including the logistics of acquisition and storage, ethical concerns, and the overall poor emulation of In vivo conditions. For this reason, researchers have actively sought alternative solutions for surgical training through rapid prototyping [20].

These ‘surgical training phantoms’ offer a better understanding of patient specific anatomical abnormalities and are useful in helping determine the best treatment for a given pathology. Additionally, these tangible 3D models are effective tools in simulating in vivo conditions without the risk to patients or at the cost of a cadaver [21]. Devising a means of 3D printing patient specific anatomical models which can be deconstructed to reveal complex internal anatomy would be beneficial as a training tool for aspiring clinicians; or indeed anyone interested in understanding the inner architecture of a specific internal organ.

Surgical Planning

Just as surgeons-in-training can utilize 3D printing to acquire tools for training, surgeons themselves are able to employ 3D printed medical imaging data to help plan patient-specific operations. During pre-operative planning, surgeons are able to use 3D printed anatomical models to foresee any complications based on structural aberration and adjust the procedure accordingly [22].

Some procedures are reliant on the creation of physical models of internal anatomy (such as the deployment of aortic valve stents). Traditional casting methods are difficult and time consuming; however the models are necessary to properly shape the stent and aide in navigating its deployment. Using a commercially available 3D printer, researchers were able to generate the necessary model in a single step, drastically reducing the amount of time required to cast the model using traditional means [23].

In comparison with medical visualization data presented on a 2D screen, 3D printed anatomical models make examining distances and relationships between structures much easier. Because the scale of the physical models can be matched to that of the patient, they are ideal for surgical planning. Objects can also be printed in flexible materials which can be used to simulate both the material composition as well as the physical behavior of the anatomy it represents [24]. The ability to study the interior of printed anatomy without compromising aspects of the structure's exterior would benefit surgical planning in that both the interior and exterior structures could be analyzed using a singular model.

Prosthesis Design

Medical researchers have also recognized the nascent potential for prosthesis design inherent in 3D printing. Because complexity is essentially free in additive manufacture techniques, the possibility for infinitely customizable designs becomes a reality. When utilized in tandem with highly accurate, patient-specific medical imaging scans; 3D printers are capable of generating prosthetic devices custom tailored to the individual patient & their disability.

These techniques have been widely used for replacing lost or damaged bone material, such as in facial reconstruction. Hip, femur, and knee reconstructions have also benefited from 3D printing techniques [7]. However, 3D printing from medical scan data for prosthesis design is not limited to rigid anatomical structures. Soft tissue prosthetics have also been designed. Notable examples include auricular prosthesis [25] and even pulmonary heart valves [26].

Regardless of tissue type, 3D printed anatomy derived from medical scan data acts as an enormous boon to the design and manufacture of prosthetics. In the case of cardiovascular surgery in particular; having access to the interior structures of the printed anatomy would allow the prosthetics to be test fit to the patient's anatomy pre-operatively, allowing for optimal design and placement of the prosthetic device. Such a tool could also offer distinct advantages in doctor/patient communication and in the gathering of consent.

Diagnostic Imaging

Perhaps the most profound use for 3D printing of medical imaging data exists within its potential as a diagnostic aide. As previously mentioned; significant perceptual gaps are inherent in three dimensional medical imaging data presented in a two-dimensional format. For this reason, pathologies or aberrations which might be obvious in a tactile physical object may become obfuscated when presented on a flat, two-dimensional screen. These constraints can be easily overcome through 3D printing regions of interest in CT or MRI scans.

This approach is particularly useful in the area of cardiovascular healthcare due to the complexity of the heart and its inherent importance in overall physiological function. For this reason, it is of paramount importance to cardiologists that they be able to obtain highly accurate imaging data through non invasive means. Because of the complex three-dimensional relationships present in structural heart defects, 3D imaging modalities are severely constrained by 2D output displays [11].

In addition to the haptic feedback and spatial understanding that 3D printed imaging data makes possible, it is also able to provide valuable information about the complex functions that take place within the heart. One research team was able to utilize rapid prototyping of the thoracic aorta to analyze the accuracy of 3D printed vascular models. This was achieved by creating identical vessel geometry to that of in vivo conditions and comparing the fluid dynamics of both systems. The researchers concluded that the 3D printed models were highly accurate in conveying in vivo conditions, and can be used to model complex dynamics that take place within the heart [27].

By 3D printing medical scan data of the heart, cardiologists have been able to correctly identify structural defects in patients preoperatively using 3D printed models derived from MRI data, then correctly confirm and treat the abnormalities during surgery. Researchers describe the three-dimensional context provided by the printed models as “unequivocal”, citing that the information they provided was “invaluable in supporting the surgical decision making” [15].

Regardless of the intended application or utilized approach, those who have performed research into 3D printing from medical imaging data recognize the difficulty in image processing. Once the MRI or CT scan data has been procured, significant effort must be spent by a skilled 3D modeler to convert the data to a printable 3D model [7].

3.4: Doctor/Patient Communication

Within western medicine, it is widely agreed upon that patients should be both well informed about available health care options, and should be active participants in making decisions about the care they receive [1]. For this reason, it is essential for physicians to provide patients with a balance of easily digestible information about their illness (prognosis) while opening discussion about positive steps toward managing the illness (treatment)[3]. Because the patient’s wishes are the deciding factor, it is important that effective information and guidance are provided to the patient during the decision making process [2].

Rodriguiez's study into cardiac patients' knowledge regarding heart failure diagnosis sought to qualitatively gauge the patient education these individuals received. The study was grounded in the idea that "patient education is central to the management of individuals with heart failure". The study concluded that patients were not receiving adequate information about their prognosis, and that they ultimately suffered from a lack of understanding about their underlying illness [3].

When diagnosed with a life-threatening heart condition, patients are faced with the daunting task of providing consent for whatever procedures or interventions their doctor may recommend. According to one study [5], there are three existential concerns patients face when asked by their doctors to provide consent for high risk cardiac procedures. These include 1) uncertainty about survival, 2) negotiation of responsibility, and 3) placing trust in the doctor's proficiency. These concerns are not reserved for the patient alone, the patient's doctor must face them as well.

When consulting a patient about a high risk cardiac procedure, a doctor is tasked with quantifying the associated risk to the best of their ability. Often, there is a high level of uncertainty about these inherent risks. Doctors are obligated to explain not only the risk of undergoing a suggested procedure, but also the risks associated with foregoing treatment altogether. Ultimately, the patient must weigh both sides of the dilemma in order to make a decision about whether or not to undergo treatment.

This presents doctors and patients with the complex and delicate undertaking of negotiating responsibility. In some instances, the patient is obliged to leave the decision making responsibility with the doctors. These patients believe the choice should be made by the doctor, as their knowledge and expertise would guide them to the right decision about whether or not to perform a procedure. In these situations the doctors must redirect the decision making authority back to the patient. Ultimately, the doctor is in charge of informing the patient of risks while the patient is in charge of deciding if they are willing to undergo a procedure in light of said risks. Because of this, it is crucial that doctors are able to provide useful and insightful information to patients in a way that is easily understood. The more informed the patient is about their condition and the inherent risks of treating it, the less they are burdened by their responsibility to choose whether or not a treatment is appropriate [5].

The burden of this decision making process is eased somewhat through the use of Decision Making aids [6]. These aids contain relevant information about a given pathology, available treatment options, and other information intended to raise the health literacy of the patients in question.

One drawback of these aids is the antiquated formats in which they are often delivered. Routinely taking the form of paper pamphlets or brochures, or at best interactive web platforms, these aids fail to utilize the advanced visualization techniques employed by other areas of medicine, such as interactive surgical training or 3D simulations [17, 28]. This is partially due to the immense effort required to develop such highly sophisticated visualizations, especially if they are to be highly accurate and patient specific.

This research proposes that 3D printed cardiac models will overcome the limitations associated with contemporary visualization aids, and will facilitate the communication process between doctors and patients by providing physical replicas of patient specific scans that can be manipulated tactilely. Previous sections in this literature review have documented numerous cases instances where doctors are already employing 3D printed cardiac anatomy models to aid in making decisions about treatment. Given the importance of the decision the patient is tasked with making, this thesis suggests that 3D printed cardiac anatomy models can be just as beneficial to the patient.

IV. PROJECT OUTLINE

Figure 1: Proof of Concept Print (left) and Final Result Print (right)

As previously described, the process for deriving a 3D printed model from medical scan images exist in 3 basic steps; 1. Image Acquisition, 2. Proccessing/Segmentation, and 3. 3D printing. This section provides specific information about the approach utilized for this research project in particular, and includes descriptions of the processes employed for both the proof of concept model and the final result, as two separate approaches were used for each. Many different tool paths/work flows exist to facilitate the transition of CT image to 3D printed model, the workflow described here is merely one available option.

Image Acquisition

Both the proof of concept model and the final model were derived using DICOM datasets acquired from the DICOM sample image sets made available on the www.osirix-viewer.com/datasets/ website. The proof of concept model utilized the ARTIFIX images (CT), while the final result was based on the AGECANONIX (CT 16) image set. Both series have been stripped of any identifying patient information, and are made available exclusively for research and teaching purposes.

Processing/Segmentation

The proof of concept model was derived using the Osirix DICOM viewer software. A volume render of the thoracic region was generated from the CT image. The cardiac anatomy was then segmented in 3D by deleting unwanted voxels from the overall volume render. A 3D mesh of the remaining data was exported as an .obj. Meshlab, an open source 3D mesh processing software system, was then used to finalize the mesh and convert it to the necessary .STL format for printing.

The final model was segmented using Mimics Innovation Suite 16.0. This software was chosen for the advanced level of control afforded when working with medical imaging data as well as its native support for 3D printing preparation and .STL formatting.

The segmenting process begins by defining a “mask”, or a selection of pixels based on a contrast threshold within the medical imaging data. The mask is then further refined to include only the desired structures depicted in the scan, in this case the interior and exterior sections of the cardiac anatomy. This refinement process included removing the extraneous anatomical structures of the mediastinum (e.g. the esophagus, trachea, and bronchi), while ensuring that as much detail as possible be included in the heart’s interior sections. This was done by segmenting the myocardium (muscular tissue) of the heart. Once a complete mask of the myocardium has been generated it is used to calculate a 3D mesh. This mesh is then ready for export in the .STL format.

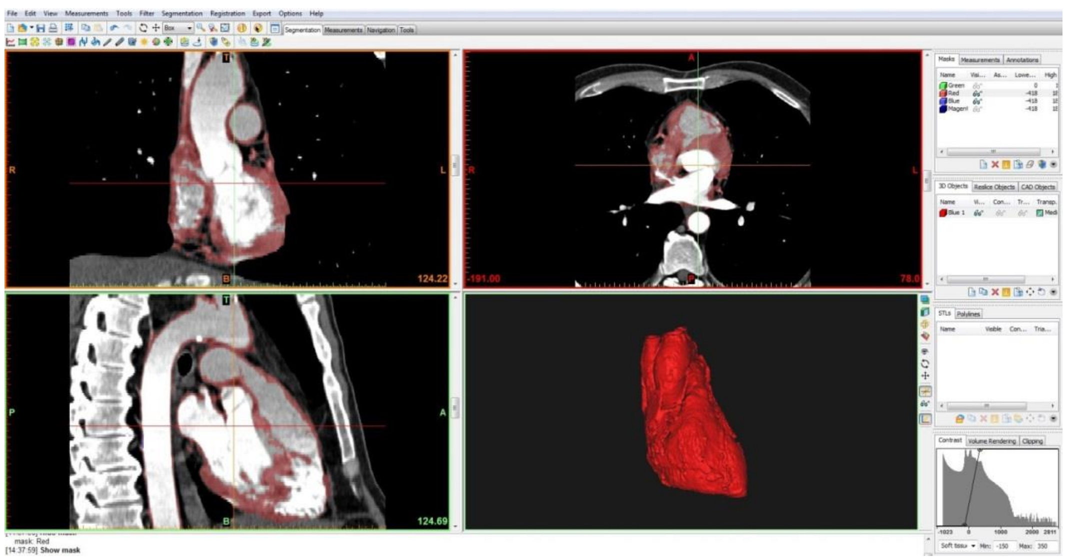

Figure 2: Segmentation in Mimics Innovation Suite

While the core module of the Mimics software includes robust segmentation and functionality, additional modules are required to complete more specific 3D printing tasks, like sectioning along a singular plane, and advanced mesh cleanup. Because access was limited to the core module during this research, additional tools were employed to complete the processing and segmentation tasks.

In order to ensure that the model generated from CT imagery is printable, it is first imported to Meshlab. Meshlab is used to reduce the number of polygons that comprise the 3D model from roughly 2 million faces approximately 250,000 faces. This lower polygon count will make the model more manageable for 3D printing. The reduced polygon mesh is then imported into Netfabb, a software package which "repairs" 3D models for printing. Netfabb essentially checks to ensure that the model is free from errors such as non-manifold faces, errant vertices, and gaps in the mesh.

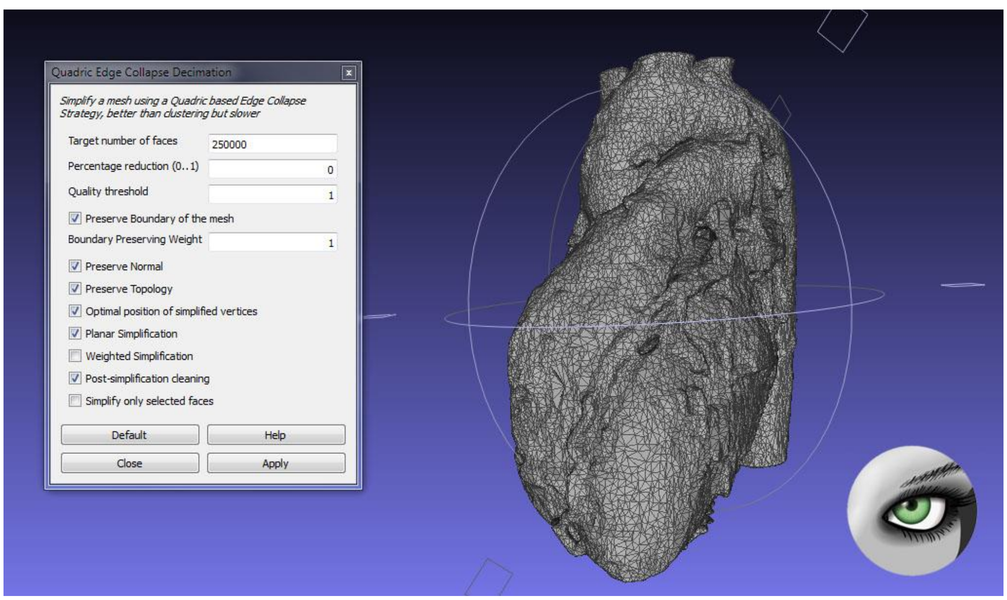

Figure 3: Quadratic Edge Collapse Decimation

Finally, the model is opened with Autodesk Meshmixer. Meshmixer is a free tool for mesh manipulation and 3D printing preparation. Meshmixer was used to section the heart model along a single oblique planar axis. This allows for visual access to the interior chambers of the cardiac replica. The planar section applied to the model used in this research was based on the planar section illustration included in F. Netter's Atlas of Human Anatomy.

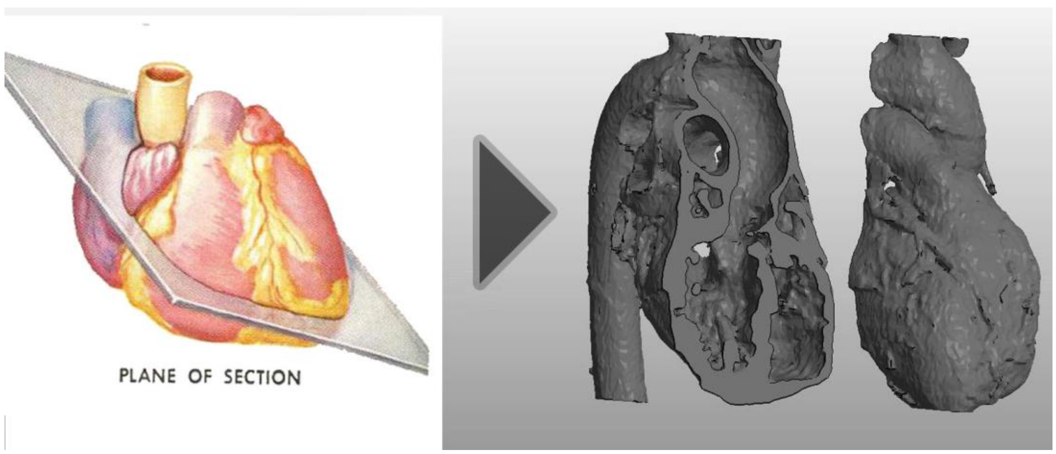

Fig. 4: Single Planar Sectioning

Because the plane of section can be placed arbitrarily, any planar section desired is possible, including multiple sections. Meshmixer was chosen for this task because it allows users to easily place the plane of section in any position in 3D space. Once sectioned, it automatically generates the necessary geometry to maintain a contiguous structure.

While Meshmixer, Meshlab, and Netfabb allow for easily accessible options for advanced processing techniques prior to 3D printing, such a fragmented tool path is not ideal. It is however possible to achieve all of the functions described above through the use of additional modules for Mimics. The additional tools listed here were used in lieu of access to those modules.

3D Printing

The proof of concept model was printed using a CubeX desktop 3D printer. The CubeX uses FDM (fused deposition modeling) technology whereby heated thermoplastic is deposited in layers to create the final model. The model was printed several times in a singular piece without planar sectioning applied. It was reduced in scale by 55% to reduce material consumption and time required for manufacture, and was printed at a .25mm layer height. The completed proof of concept cardiac replica took a total of 8 hours to print, with a further half hour required for removal of support material.

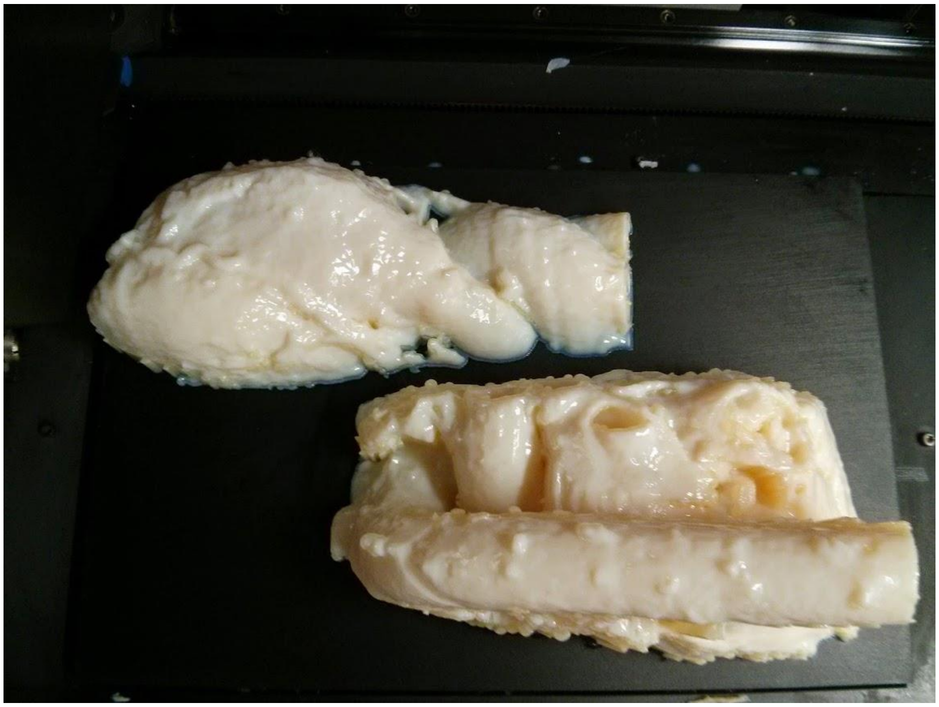

Figure 5: Completed Print on Objet 30

The final model was printed on an Objet30 polyjet printer. The Objet30 deposits UV-curable resin at 16-micron layer heights. The model is supported during printing using a waxy support material that is water soluble. When compared to FDM modalities, the removal of support material is much less destructive. The final completed cardiac anatomy replica took a total of 24 hours to print at 100% scale in two (simultaneously printed) sections, with an additional hour required for removal of support material. Due to the non-destructive support material, superior resolution, and virtually imperceptible layer stratification afforded by the Polyjet process, it is by far the better choice for printing cardiac anatomy replicas where precision of detail and accuracy to scan data are crucial.

V. METHODOLOGY

This research aims to assess the effectiveness of patient specific 3D printed cardiac anatomy replicas in aiding traditional visualization techniques for the purposes of doctor/patient communication. To do this, a 3D printed cardiac anatomy replica was derived from CT imaging data using the techniques described in the previous section. In order to assess the cardiac anatomy replica’s efficacy in aiding traditional visualization tools, qualitative analysis was conducted by consulting an expert panel of doctors from diverse backgrounds, including cardiologists, radiologists, researchers and surgeons. The expert panel was selected by consulting existing contacts within Drexel University’s College of Medicine. Additional panel members were contacted through primary panel members by way of snowballing, and in the case of one panel member, recruited in person while at the 2014 Mimics Innovators Conference. Each member of the panel was a valuable addition based on their vast cumulative expertise in cardiac medicine as well as their unique perspective given their individual medical disciplines. The expert panel members include:

- Dr. Thomas Foley, M.D., *Cardiothoracic Radiology*, The Mayo Clinic
- Dr. Cheryl Hanau, M. D., *Chair, Dept. of Pathology*, Drexel University College of Medicine
- Dr. J Yasha Kresh, Ph. D., *Research Director, Cardiovascular Surgery/Biophysics,* Drexel University College of Medicine
- Dr. Glenn Laub, M. D., *Chair, Cardiothoracic Surgery,* Drexel University College of Medicine
- Dr. Kathleen Ryan, M.D., *Director, Medical Simulation,* Drexel University College of Medicine
- Dr. Arnold Smolen Ph. D., *Associate Dean of Information Technology,* Drexel University College of Medicine
- Dr. Beth Zigmund, M.D., *Section Chief, Cardiothoracic Imaging,* Hahnemann University Hospital

The panel members each participated in a semi-structured interview in a one on one setting with the researcher. A semi-structured interview format was chosen in an effort to cultivate a dialogue between the researcher and the panel members. The goal was to not only allow the individual panel members' perspectives guide the conversation, but also to accommodate for variations in a given panel member's existing knowledge of the 3D printing aspects of the research.

Each panel member agreed to participate in a 30-40 minute interview session. Six out of Seven panel members consented to have the conversations recorded. The interviews began with an overview of the research being conducted and an explanation of the open ended interview structure. Panel members were invited to ask questions and offer suggestions as they saw appropriate and encouraged to explore avenues of discussion I might not have considered.

During the interviews, the interviewee had access to the 3D printed cardiac anatomy replica, as well as the DICOM series from which it was derived available for comparison. The interviews were loosely structured around a discussion outline that covered a range of topics based on the research question: *How can patient-specific 3D printed cardiac anatomy models supplement contemporary visualization techniques in aiding Doctor/Patient communication?* Some discussion points were covered in more or less detail depending on a panel member's responses based on their area of expertise or previous experience, and some topics arose naturally that are not included in the discussion outline. The Discussion Outline includes the following questions and potential follow-up questions:

- Frequency of communication with patient or medical laypersons?
    - How often? What are the associated difficulties? What aids do you employ?
- Accuracy of print in depicting the anatomy?
    - Anything missing or unclear? Any obvious issues with the scan or the segmentation?
- What potential pathologies could the cardiac anatomy replicas be used to depict?
    - Are these pathologies time sensitive?
- Is there potential for clinical integration of cardiac anatomy replicas?
    - Do you have a clear understanding of the workflow? Can you think of cases where they might have been useful?
- What are areas of further development that might benefit cardiac anatomy replicas?

- What is missing that would be helpful to see?

Each question in the discussion outline is designed to correlate directly with an aspect of the overall research question. Questions about frequency of communication with laypersons establish an understanding of that panel member's perspective on doctor/patient communication. The accuracy of the print in depicting the anatomy and the potential to depict pathology speak to the replica's validity as a supplement to existing aids, while inquiries into clinical integration and desired future developments address potential concerns associated with the practical implementation of patient specific cardiac anatomy replicas as communication aids.

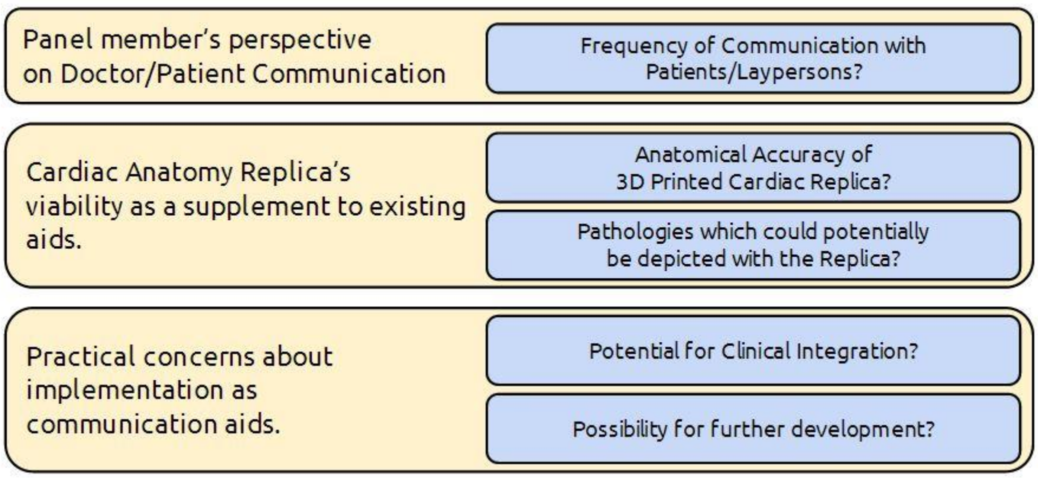

Figure 6: Relationship between Research Question and Discussion Outline

After completing the interview process, the audio recordings of six of the seven interviews were transcribed. Three of the transcriptions were done by the researcher, the other three were done by a professional transcriptionist who volunteered their time to assist this research. The interview notes, audio recordings, and transcriptions were then reviewed using the rubric for correlation described in the previous paragraph. Under this lens, the qualitative feedback provided by the expert panel, an answer to the research question can be synthesized. The following section provides a detailed summary of the results of that synthesis.

VI. RESULTS

Each of the interview recordings were reviewed according to the Discussion Outline and its correlation with the Research Question. The expert panel’s overall responses to each area of the discussion outline are summarized below.

Frequency of Communication with Laypersons:

Each interview began with questions about the expert’s frequency of communication with patients or laypersons. While this research is primarily interested in discovering how cardiac anatomy replicas can improve doctor/patient communication, it does so from the perspective of the doctors, as they assume the role of information giver in the conversation with patients, the burden is on them to make the information clear. It is therefore important to establish an understanding of how often each expert in the panel is in a position to communicate with patients or other medical laypersons.

The frequency at which the individual panel experts communicate with actual patients varied significantly. Roughly a third of the panel members are practicing physicians and are in a position to speak with patients on a regular basis. The remainder of the panel are either in research or radiological roles, and interface with the doctors treating the patients. Nearly the entire panel also teaches students in their field of expertise, and drew upon that experience where bridging knowledge gaps about anatomy and medicine are an everyday occurrence. What became evident after conducting the interviews is the number of times the medical information must be communicated en route to the patient. Radiologists are responsible for delivering vital information learned from the scan data in a report to the doctors. Surgeons must exchange information in order to successfully plan and carry out interventions. Doctors must also communicate medical information to patients and their families. Meanwhile, medical students who are training to become doctors are also in need of clearly digestible information. Simply put, doctor patient communication is much more than a two way dialogue; there are many individuals involved in making sure the patient gets clear and useful information.

Panel members were also asked to speak about the types of aids they employed to communicate medical information to these patients and laypersons. They were also asked to discuss any difficulties that commonly arise while using these aids. A variety of types of visualization aids were used by the panel to assist in communicating medical information. Of the panel members who speak directly with treating physicians, CT scan data itself is often used. In some cases, 3D representations based on the CT scan were used as well. One member of the panel, a cardiothoracic radiologist from the Mayo Clinic already uses 3D printed cardiac anatomy models to communicate findings with doctors. Another panel member, a cardiothoracic researcher from Drexel University College of Medicine, keeps non-patient specific cardiac anatomy models on hand for quick access to three dimensional, tangible reference materials.

Those that use CT scan images to communicate medical information to colleagues and patients agree that there is often difficulty understanding the spatial relationships when looking at the fragmented CT data with an untrained eye. In one case, the panel member described occurrences where the doctor will have difficulty delineating relevant structures in the grayscale scan data, or might find the contrast agent within the vessels distracting. 3D volume renders are sometimes used, but again they are restricted to two dimensional viewing formats.

Other panel members who primarily communicate medical information to students use other types of communication aids. Either photographic/xray/or graphical visualizations are used to convey information frequently. In some cases where changes over time are to be depicted (one panel member spoke about this in regard to embryology, including cardiac embryology), 2D and 3D animations are sometimes used. The same panel member spoke to the use of cadavers in teaching gross anatomy, as it is advantageous because it involves handling the anatomy as well as looking at it visually; "getting all of the senses involved", as the panel member put it.

Regardless of the mode of communication aid, the difficulty of communicating 3D problems using 2D information was a recurring theme throughout the interview process. The one panel member who has experience using 3D printed cardiac models in practice attested to the added value that the physically tangible representations provide. Nearly all members of the panel agreed that a tangible model would be superior to any two dimensional means of conveying CT scan data.

Accuracy of 3D Printed replica in representing the anatomy

During each interview, the panel members had full access to the 2D CT scan data from which the 3D printed cardiac anatomy replica was derived as well as the 3D printed cardiac anatomy replica itself. Each panel member was questioned regarding the accuracy of the printed model in presenting the anatomy in the scan data. Any inconsistencies or gaps in information were attributed to either issues with the scan (shortcoming in the modality) or issues with the segmentation (shortcoming in the 3D model generation process). By verifying the accuracy of the 3D printed cardiac anatomy replica in accurately conveying anatomy, it can be reasonably argued that the 3D representations of the scan are as trustworthy in conveying information as the scans themselves.

Again, the panel was nearly unanimous in verifying that most of the major structures of the anatomy were apparent in the 3D printed model. Several of the panel members were very satisfied with the anatomical representation depicted by the 3D printed model. Overlapping feedback includes positive comments about the interior detail, including the depiction of the papillary muscle. Every panel member was able to correctly identify the major chambers and vessels presented in the model. More than one panel member used highly expressive positive language to describe the print's accuracy, calling it “an amazing representation” and “incredibly accurate”.

A few panel members, on the other hand, expressed concern over the “roughness” of the exterior aspects of the print (caused by noise within the scan data), and the absence of the internal valves (difficult to depict with CT). Some issues with the segmentation itself arose, including extraneous data being captured around the auricle, and poor separation between the right ventricle and atria. While a majority of the feedback on the model was positive, these recurring criticisms suggest areas for improvement in both the scan data acquired and the segmentation itself. In the words of one panel member, the anatomical representation of the cardiac anatomy replica was “good, not great”.

Another common criticism of the model that arose was that it included too much detail. Several panel members commented that while a physician or radiologist is trained to “filter out” superfluous information in the represented anatomy, this might not be the case with patients or laypersons. It was argued by many of the panel members that a more simplified model depicting only the major landmarks and areas of interest of the model would be more beneficial in conveying information to patients. Achieving a less noisy and more simplified model is certainly an achievable goal using a more aggressive segmentation approach and a higher resolution dataset.

Despite these few common criticisms, the panel largely agreed that the 3D printed car7diac anatomy replicas were sufficient representations of the anatomy depicted in the source dataset. What issues did arise with the model are either a product of the scanning modality and thereby unavoidable, or are easily corrected with minor adjustments during segmentation, and by using scan data more in line with current standards (as would be the case in a clinical setting).

Potential for depicting pathology

Though a healthy heart specimen was depicted in the 3D printed cardiac anatomy replica used in this study, in cases of doctor patient communication there would obviously be some defect or pathology that would give cause for concern. After reviewing the 3D printed cardiac anatomy replica, panel members were asked to speak to potential pathologies the replicas could be used to depict.

The panel was nearly unanimous in many of the pathologies it mentioned being strong candidates for 3D printed visualization. Mentioned most were atrial and ventricular septal defects, cardiomyopathy, as well as other common congenital issues. A few panel members suggested that cardiac anatomy replicas would be useful for survivors of myocardial infarction to depict necrotic tissue after the event. Other pathologies mentioned were aortal aneurysms and cases where ventricular assist devices might be necessary.

The panel member who already uses 3D printed cardiac anatomy replicas in practice as a cardiothoracic radiologist reported that the models have been most useful for congenital cases of arterial anomalies in the chest, the main one being pulmonary atresia. While less cases have occurred in his practice, he is also interested in exploring the depiction of cardiac masses using 3D printed cardiac anatomy replicas, and in cases of valve replacements where a prosthetic is already in place, requiring a “valve in valve” procedure.

Obviously, time is a limiting factor with some pathologies. If a case were significantly emergent, there would not be enough time to print a heart for consultation beforehand. However, given the wide variety of potential pathologies suggested by the panel, and the significant overlap between many of the pathologies mentioned; it can be surmised that 3D printed cardiac anatomy replicas would be useful in a number of circumstances where doctor/patient communication would be required to decide upon an intervention.

Potential for Clinical Integration

If doctor/patient communication is to be supplemented by 3D printed cardiac anatomy replicas, it is crucial that they be available to patients in the first place. This means that the process for deriving the models be viable for clinical integration. For this to be possible, certain logistical concerns must be addressed. Panel members were asked to discuss the potential for clinical integration of the 3D printed cardiac anatomy replica, as well as any limiting factors that might prohibit it.

All but one member of the panel were confident that the 3D printed cardiac anatomy process is not only viable for clinical integration, but would be a useful addition. The one surgeon who questioned clinical integration of the 3D printed cardiac anatomy replicas reported that “90% of the cases I treat consist of 3-5 types of surgery”, and that in most cases achieving consent from the patient is not an issue. According to this panel member, in the few unusual cases where the patient does need convincing, while useful; the value added would not be worth the investment.

Despite this, the rest of the panel strongly agreed that 3D printed cardiac anatomy models would be a useful addition in a clinical setting. A large majority of the panel also agreed that the models would be useful for teaching medical students and residents about the cardiac anatomy. As mentioned previously; one member of the panel already employs 3D printed cardiac replicas to communicate radiological findings to surgeons. He reports that the inclusion of these models has shown immediate benefit to surgical planning, operating times, and overall exchange of crucial medical information throughout the treatment process.

Some limiting factors do exist in terms of clinical integration of 3D printed cardiac anatomy replicas. Firstly, the question of how to deal with inclusion into the patient’s medical records of information that exists simultaneously as digital information and a tangible object. Other concerns include how to bill for 3D printed anatomical replicas, and whether or not insurance companies will reimburse hospitals for the service. Additionally, training existing staff or obtaining new staff to handle segmentation becomes a concern, however the skills used in the segmentation procedure are not far removed from those of an existing radiological technician. The skills needed are certainly obtainable in a short time for by anyone with even limited experience dealing with CT data.

Areas for Further Development

Before concluding the interviews, panel members were asked to elaborate on aspects of the 3D printed cardiac anatomy that they thought could benefit from further development. This feedback not only addresses how 3D printed cardiac anatomy replicas could best be used to supplement doctor patient communications, it also provides insight into avenues for future research.

Much of the feedback obtained was in regard to the material properties of the cardiac anatomy replicas. The most oft repeated suggestion was for multi-colored prints. This would allow for various tissue types to be depicted, and regions of interest to be highlighted. Inclusion of “realistic color” would also make the replica more relatable to a patient or medical layperson. Another overlapping suggestion was for flexible material to mimic the behavior of the cardiac tissue.

Both of the above issues are easily addressable using existing technology and at comparable resolutions. A number of material affordances have been made possible through technical advancements in 3D printing since the introduction of the polyjet printing technology used in this research.

As mentioned previously, a large majority of the panel members suggested that when printing for communication with patients and laypersons, a more simplified replica is desirable. This too is easily addressable during the segmentation procedure. The segmentation used to derive the 3D printed cardiac anatomy replica erred on the side of faithfully rendering the information in the scan data. In future iterations adjustments could be made to the process to allow for more easily comprehensible representations of the anatomy in question.

VII. DISCUSSION

After evaluating the expert panel’s responses from the semi-structured interviews, a qualitative assessment of the 3D printed cardiac anatomy replicas’ place in the doctor/patient communication process can be made. In answer to the research question, 3D printed cardiac anatomy replicas can supplement doctor patient communication by accurately representing both anatomical and pathological information in a medium which provides both haptic and visio-spatial feedback. The 3D printed cardiac anatomy models should be rid of extraneous detail while providing as much information as possible in the region of interest, including color and textural feedback when possible.

This research also elucidated the fact that doctor/patient communication is not merely a one on one encounter. Instead, it exists as a network of physicians, clinicians, and researchers that must exchange information effectively between one another if clear information is to be provided to the patient. This research also made clear the potential for use in bridging knowledge gaps that exist outside of the doctor/patient communication paradigm. A resounding response from the expert panel was the potential for 3D printed cardiac anatomy replicas as a teaching tool for medical students. Not only are 3D printed cardiac anatomy replicas useful in educating patients, they could also be used to train tomorrow's clinicians to guide doctor/patient communication more effectively.

VIII. IMPLICATIONS

By creating patient specific physical models of cardiac anatomy derived from medical imaging data, this research provides a means to both supplement and improve upon traditional medical visualization techniques. When used as a decision aid and as a tool for patient education, the 3D printed medical imaging data should facilitate a patient's understanding of their specific ailment, and foster better informed decisions from the patient when faced with complex and often overwhelming treatment options. The 3D printed cardiac anatomy replica is useful not only when used in direct communication with the patient, but as an aid in the exchange of information between that patient's entire healthcare network.

Two processes for deriving 3D printed cardiac anatomy models from patient specific medical scan data have been exhibited; both an easily accessible free-software solution (proof of concept model) and a more specialized proprietary workflow which offers greater control and accuracy (used for the final print). These workflows can be duplicated to derive similar results for use in related research. Additionally, the process employed for this research is not limited to cardiac anatomy, nor to doctor/patient communication paradigms. Indeed, this process can be applied to any anatomical region which can be clearly depicted by CT imaging, offering enormous possibilities for research into other 3D printed anatomical replicas.

IX. LIMITATIONS

Limiting factors of this study include the difficulty in obtaining suitable CT datasets for use in the study. Due to the difficulty in obtaining suitably anonymized CT datasets, a freely available online DICOM repository was used at the expense of scan data resolution. Because the dataset used was substandard when compared to contemporary CT resolution standards (3mm vs .6mm slices), significant artifacts are present in the final segmentation that had clear effect on the responses from the panel. Access to data which adheres more closely to current standards would be desirable if more decisive results are to be obtained.

X. Future Work

Continued research in this area would benefit from improved resolution in the source datasets, as well as access to datasets which depict pathologies suggested by the expert panel. More useful results could be derived by 3D printing multiple segmentations at varying degrees of simplicity vs. detail. Additional improvements on the existing study would include access to feedback from patients who are or have been in a decision making role in regards to cardiac intervention, as well as access to more information from doctors and radiologists who have used 3D printed imaging data in a clinical setting. Expanding the research beyond cardiac anatomy into other areas of the body would also be useful in gathering data about the use of 3D printed medical imaging data in aiding patient decision making and the bridging of knowledge gaps in medicine.

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